Energy Stability in High Intensity Pulsed SC Proton Linac

A. Mosnier, CEA-DAPNIA, Gif-sur-Yvette, France

Pulsed mode operation in SC proton linac could spoil the energy stability

➥ transient beam-loading effects within a single multi-cell cavity

large beam phase slippage along the cavity and finite RF energy propagation

$\Rightarrow$ significant energy modulation with a too small cell-to-cell coupling
or a too large number of cells

➥ cavity field errors : beam phase slippage effects along the linac $\Rightarrow$ energy spread exhibits a larger sensitivity to cavity fields fluctuations than relativistic particles

MULTICELL

based on a multi-mode analysis, calculates the systematic energy modulation generated within a multi-cell cavity due to the finite speed of the rf wave propagation

PSTAB

• initially developed for relativistic beams has been extended to low beta beams

• can handle all major field error sources
(Lorentz forces, microphonics, input energy offsets, beam charge jitter, multiple cavities driven by one single power source, etc)

• includes feedback system and extra power calculation

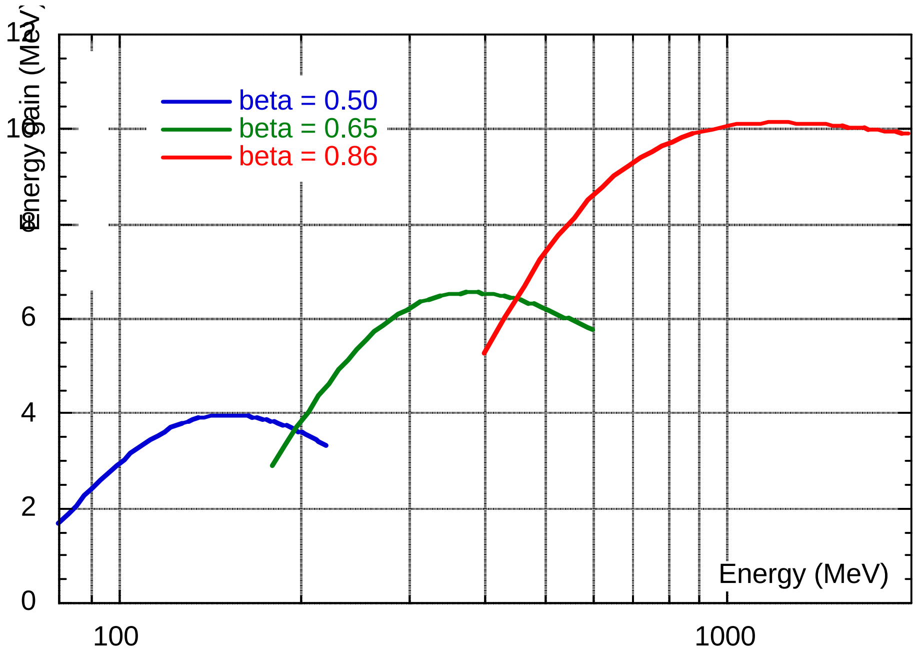
• solves the 6xN coupled differential equations, needed to describe cavity fields and beam-cavity interactions of a group of N cavities driven by one single power source

Results of simulation given for a typical neutron spallation source, like ESS

Input energy	85 MeV
Exit energy	1.333 GeV
Peak beam current	107 mA
Chopper duty factor	60 %
Bunch train period	600 ns
Number of bunch trains	2000
RF frequency	704.4 MHz

3 different cavity types have been selected from input to exit of the linac

Operating accelerating fields G correspond to electric and magnetic peak surface fields of about 27 MV/m and 50 mT.



Longitudinal beam matching between sectors controlled by adjustment of the synchronous phases of the two interface cryomodules.
The beam power per cavity ranges from 130 kW at the beginning to 680 kW at the end of the linac for the mean beam current of 64.2 mA.

	Low-β	Medium- β	High-β
G (MV/m)	8.5	10.5	12.5
Geometric β	0.5	0.65	0.86
# cells	5	5	5
# cavities /cryom	2	3	4
# cryomodules	16	14	23
Sync phase (deg)	- 30	- 27	- 25
Energy (MeV)	85 - 195	195 - 450	450 - 1348

TRANSIENT BEAM-LOADING

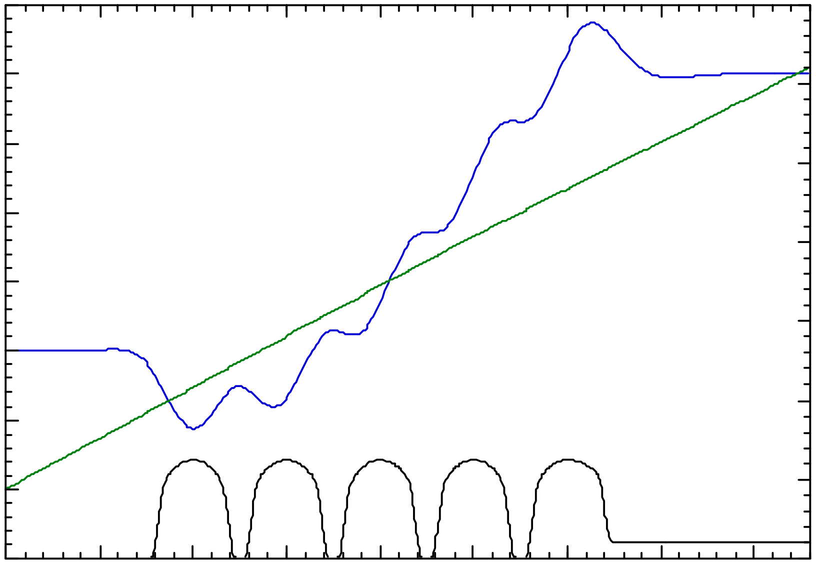
energy gain and phase slippage
(wrt a constant velocity particle, running on-crest of the RF wave) along the first cavity of the linac.

G= 8.5 MV/m ⇒ ΔE=2 MeV, integrated ϕ_b = -30°

large phase slippage

⇒ energy gains and beam induced voltages quite different from one cell to the next

⇒ large energy fluctuations for multibunch trains



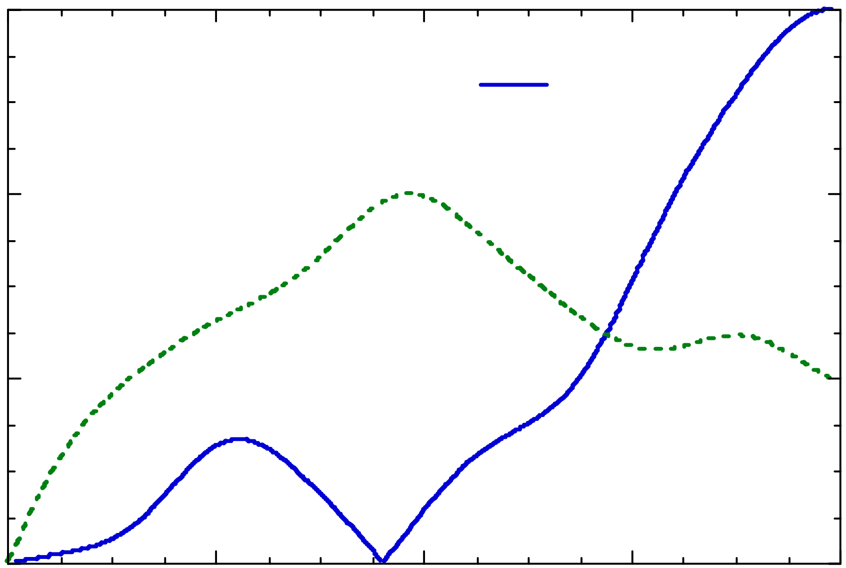
RF power propagates from cell to cell (intercell coupling) and tends to even the individual cell excitations

some fluctuation of the effective voltage remains due to the finite propagation velocity of the RF wave

Field envelopes at center of first and last cells during the filling of the first cavity

input coupler attached to the last cell

delay (about 350 ns) corresponds approximately to the group velocity of the mode in middle of fundamental passband)

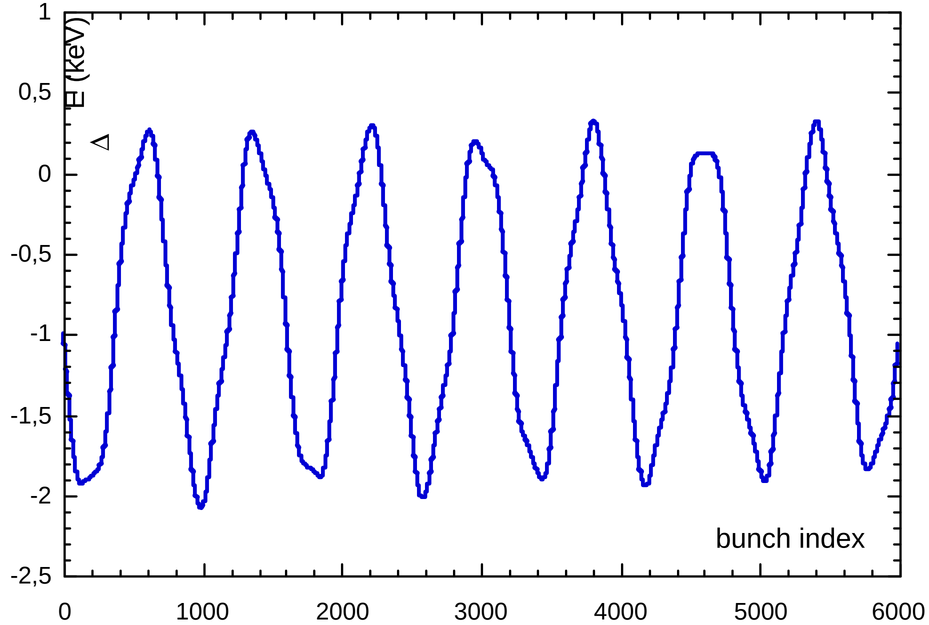


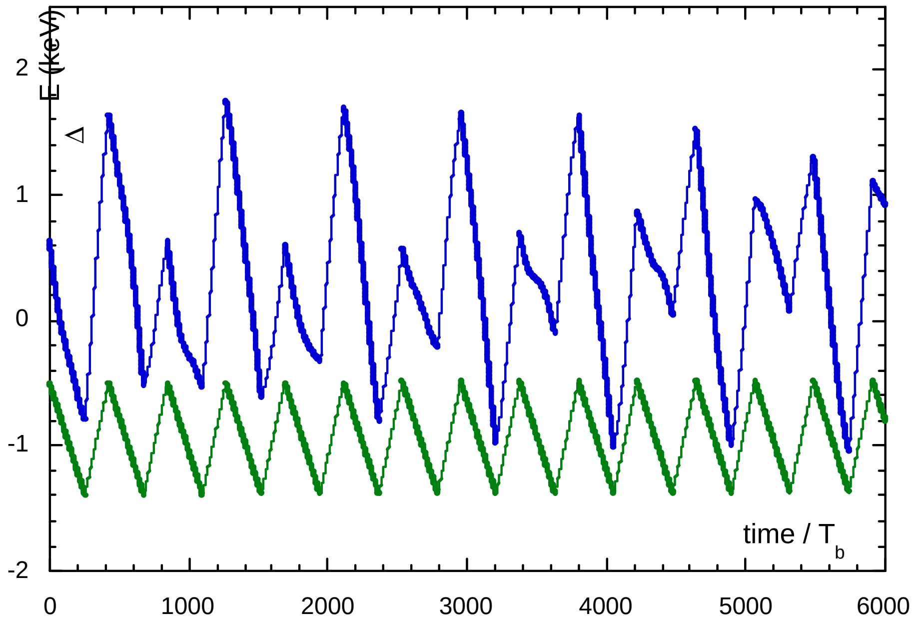
Peak beam current = 107 mA

regular bunch spacing →

resulting energy gain modulation for the first cavity ¡ 10^{-3}

residual oscillation, mainly caused by the closest mode to the accelerating Pi-mode of the passband (only 0.87 MHz apart)





← **chopped beam pulse**

cavity model = single resonator : perfect sawtooth-like voltage due to periodic beam-loading & refilling

multi-mode analysis : fluctuation follows the oscillation caused by the closest mode
systematic energy gain modulation increased by a factor larger than 3

CAVITY FIELD FLUCTUATIONS

With N cavities driven by 1 common klystron, a total of 6xN coupled differential equations per klystron is required :

- 3 equations per cavity for beam-cavity interaction

Instead of using the crude RF-gap approximation (cosine-like acceleration at the cavity middle, corrected by the transit time factor) integration of the exact differential equations in each cavity in order to model properly the beam-cavity interaction

Once the linac configuration has been defined (cavity types, number of cryomodules, design accelerating field and synchronous phase) a reference particle is launched through the linac in order to set the nominal phase of the field with respect to bunch at the entrance of all cavities

- 3xN equations per klystron for cavity field

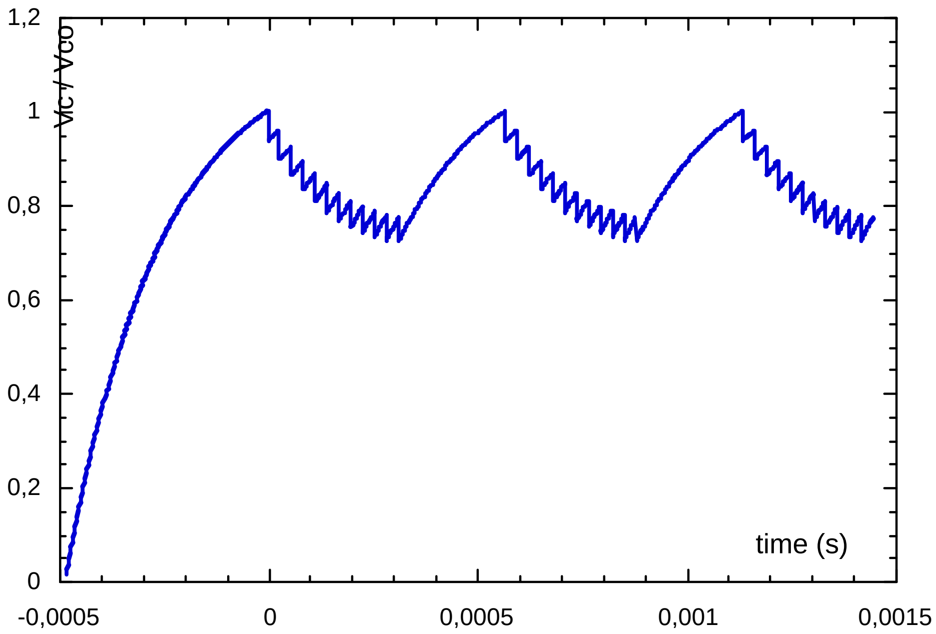
The dynamics of each resonator is described by 2 first order differential equations, plus another one modelling dynamic cavity detuning by the Lorentz forces

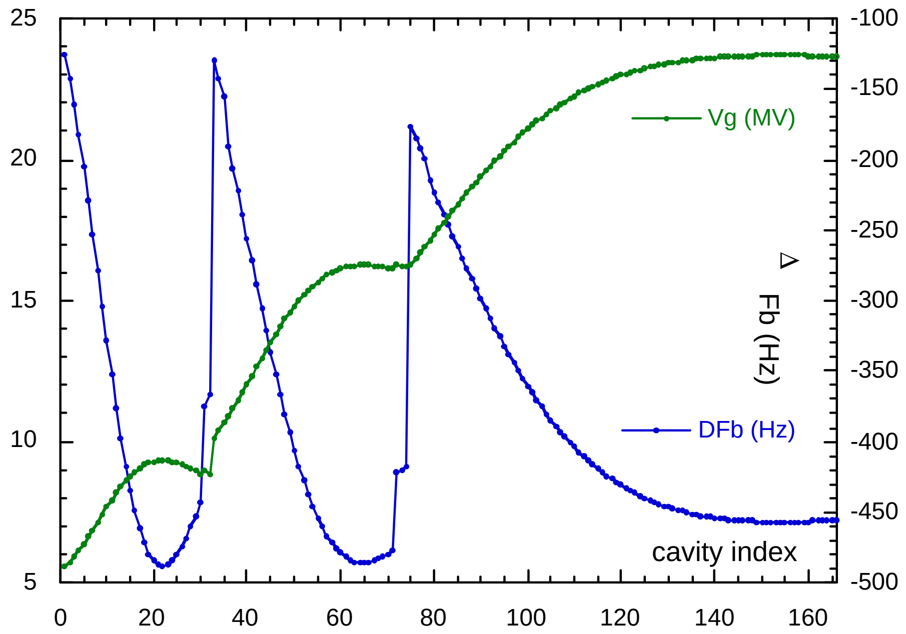
Beam-loading is modelled by a cavity voltage drop during each bunch passage with a magnitude varying from cavity to another (particle speed varies)

To minimize the needed RF power :

1) the Qex is set near the optimal coupling ¡ 5.10^5 **2)** the cavity is detuned to compensate the reactive beam-loading due to the non-zero beam phase

cavity voltage drop at each bunch due to beam-loading and re-filling between bunches due to external RF power for a chopped beam pulse
(with enlarged bunch spacing)





Generator voltage and cavity detuning must be first adjusted to recover the right amplitude and phase at beginning of each new train

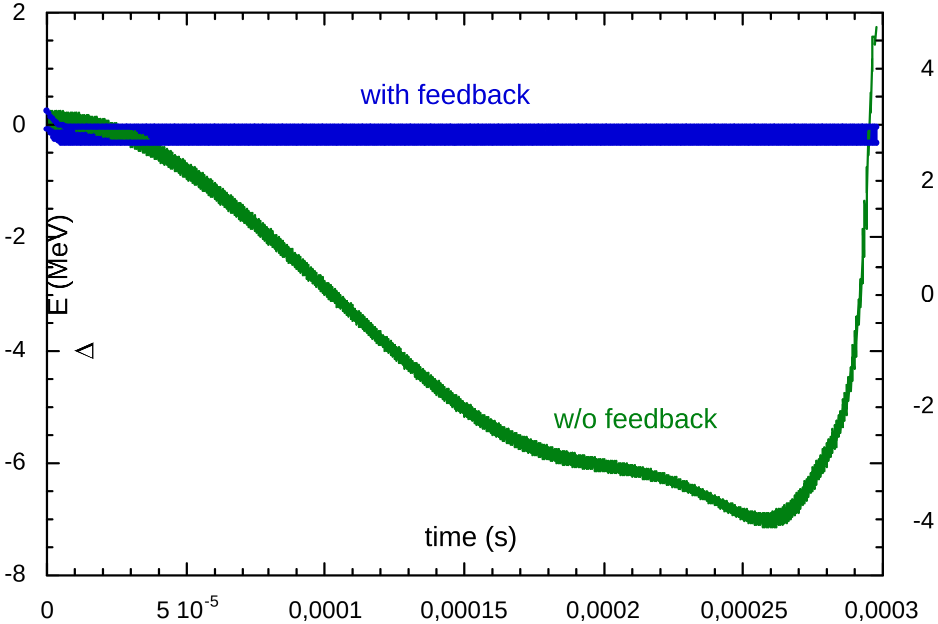
systematic voltage change due to the presence of these beam gaps ¡ 1.5 10^{-3}

One cavity per klystron

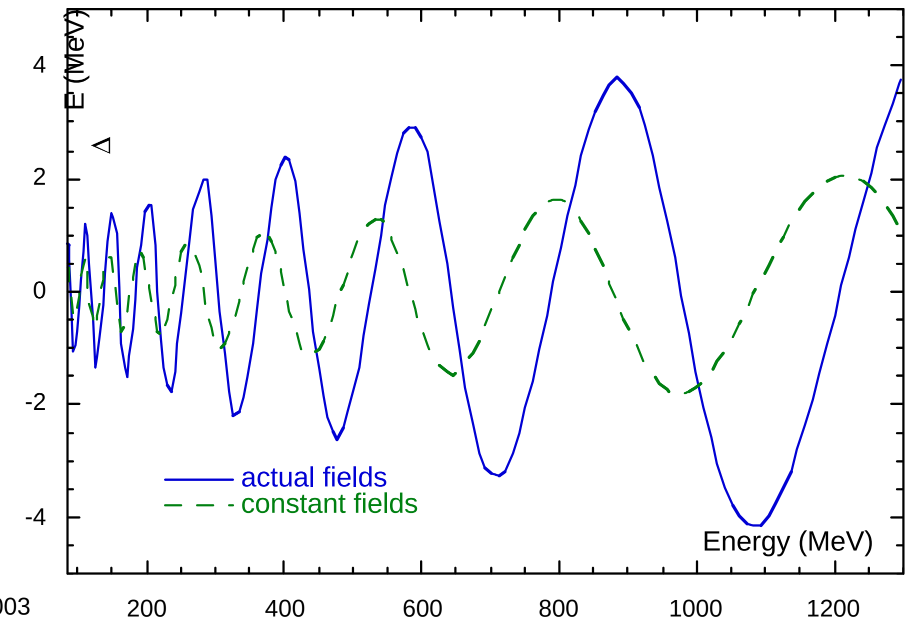
cavity voltages are controlled by modulating the amplitude and phase of the power source via an I/Q modulator
 in-phase and out-of-phase feedback loop gains set to Gi=100 and Gq=50

⇒ Input energy offset

Bunch phase oscillations induced by beam injection offsets will upset cavity voltage via beam-loading. Without feedback, the bunches become unstable very soon, while with feedback, the cavity voltages are efficiently controlled and the constant field dynamics are recovered.



Beam energy deviation at linac exit without and with feedback (0.5%)

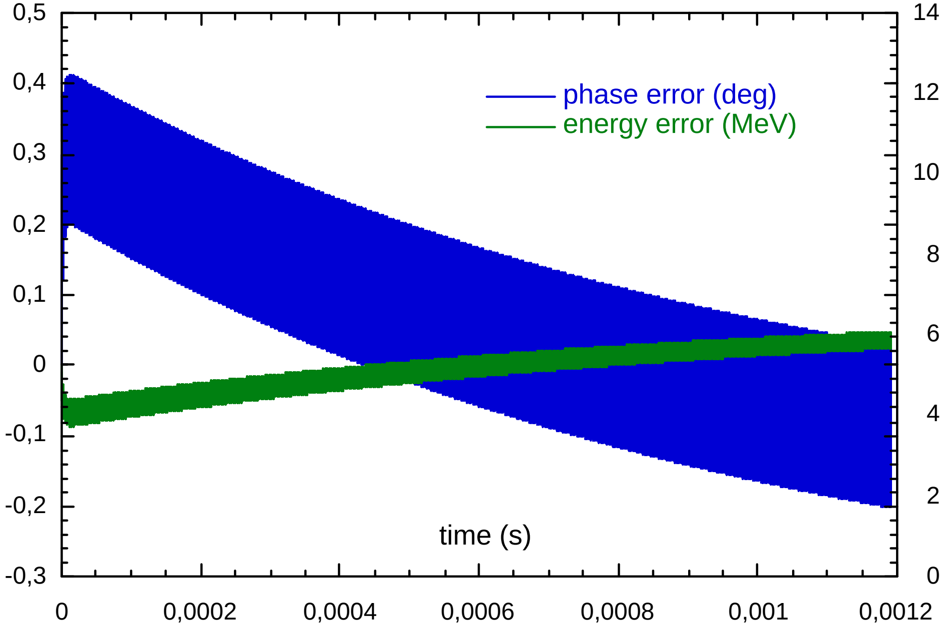


Energy deviation of last bunch along the linac for nominal and actual fields (1%)

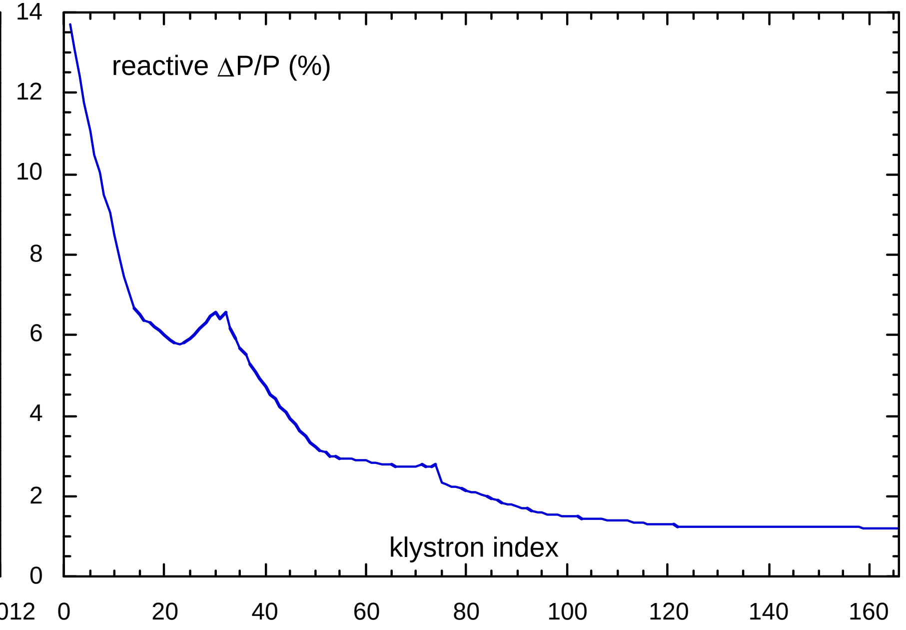
⟹ Lorentz forces effects

Because of the peak surface fields and of the mechanical rigidity of the structure, Lorentz force parameter increases as the cavity beta decreases. Simulations were carried out with expected (pessimistic) values of 16, 8 and 4 Hz/(MV/m)^2 for the β= 0.5, 0.65 and 0.86 cavity types.

In order to relax the feedback requirements, the cavity must be pre-detuned, such that the resonance frequency equals the operating frequency at approximately half the beam pulse. The total detuning must then be set to the sum of the detunings for Lorentz forces and beam-loading compensations $\Delta f_{total} = \Delta f_b + \Delta f_o$



Bunch phase and energy deviations at linac exit

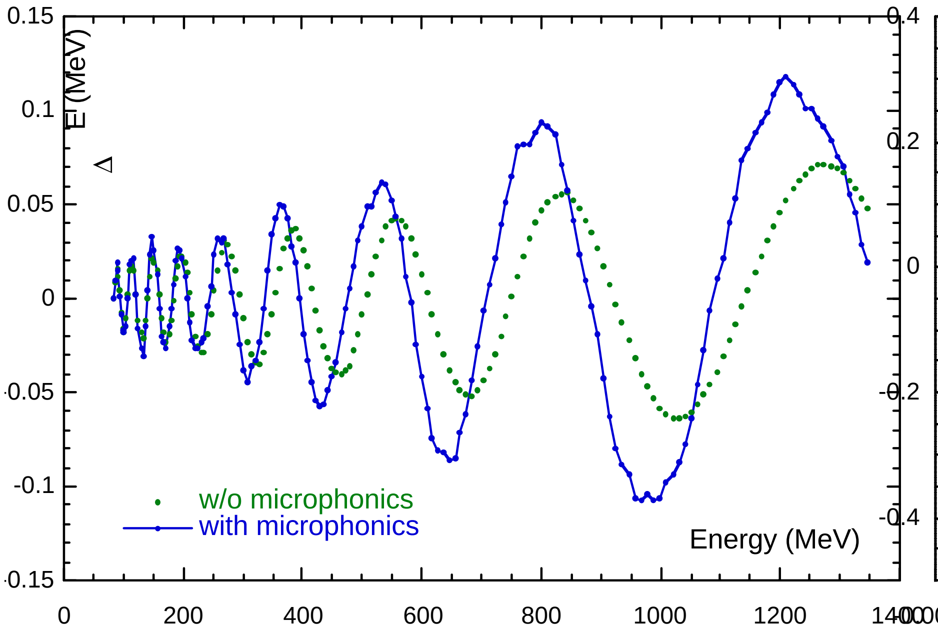


extra reactive peak power

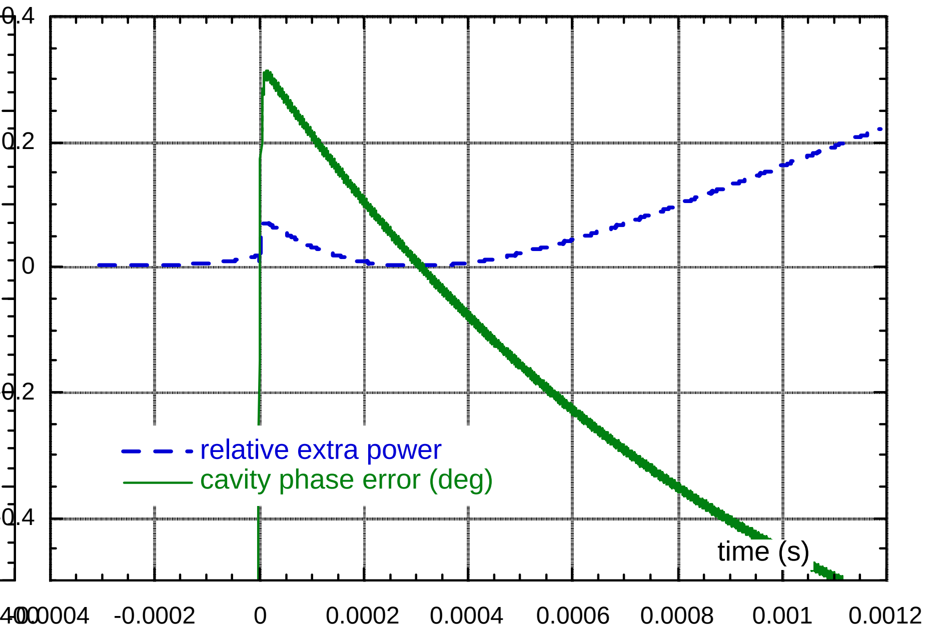
⟹ Additional microphonics effects

With mechanical vibrations, feedback loops must be closed during the filling time, following pre-determined amplitude and phase laws, to ensure minimum RF power during the beam pulse.

Assuming typical 40 Hz mechanical oscillation with an amplitude of 100 Hz (equivalent to phase fluctuations of ±8°), increase in energy deviation at linac end of about 50%, extra peak power to be paid of about 20% at the low energy end



Energy deviation of last bunch along the linac (with Lorentz forces and microphonics)



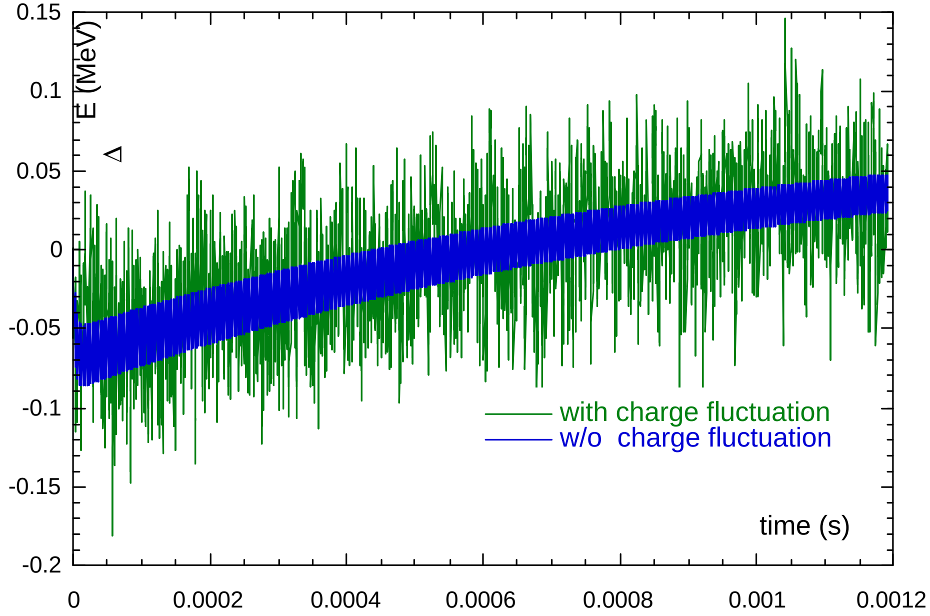
Cavity phase error & extra peak power for 2nd cavity°

(with Lorentz forces and microphonics)

⟹ Additional current fluctuation effect

With stochastic beam current fluctuation, the feedback system prevents from dramatic cumulative effects of several consecutive bunch charge errors.

A bunch charge fluctuation up to 10 % is still acceptable



Bunch energy deviations at linac exit
(with Lorentz forces + 10% bunch charge fluctuation)

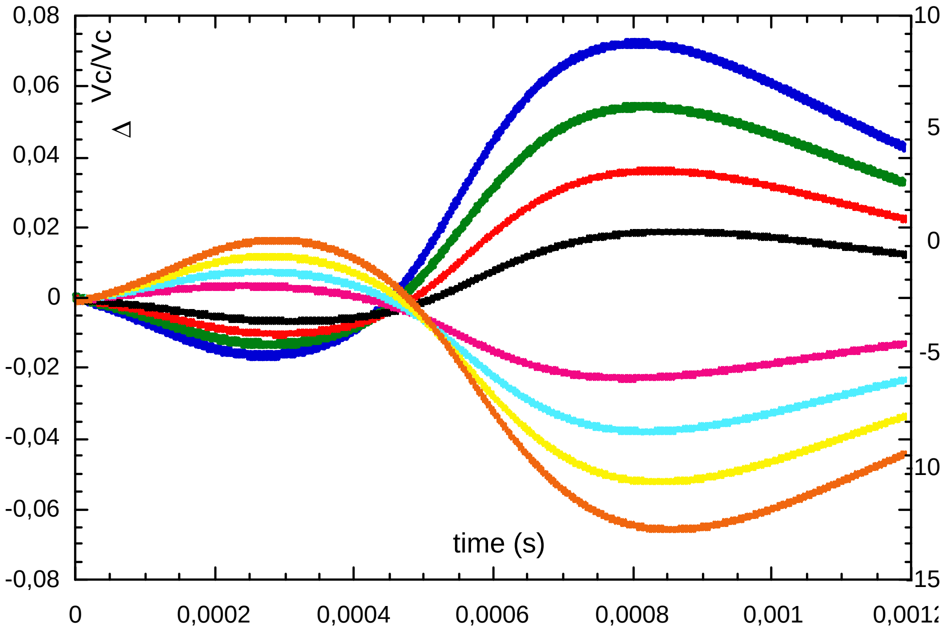
Multiple cavities per klystron

With relativistic electron beams, multiple cavities powered by a single power source can be easily controlled by the vector sum of the cavity voltages

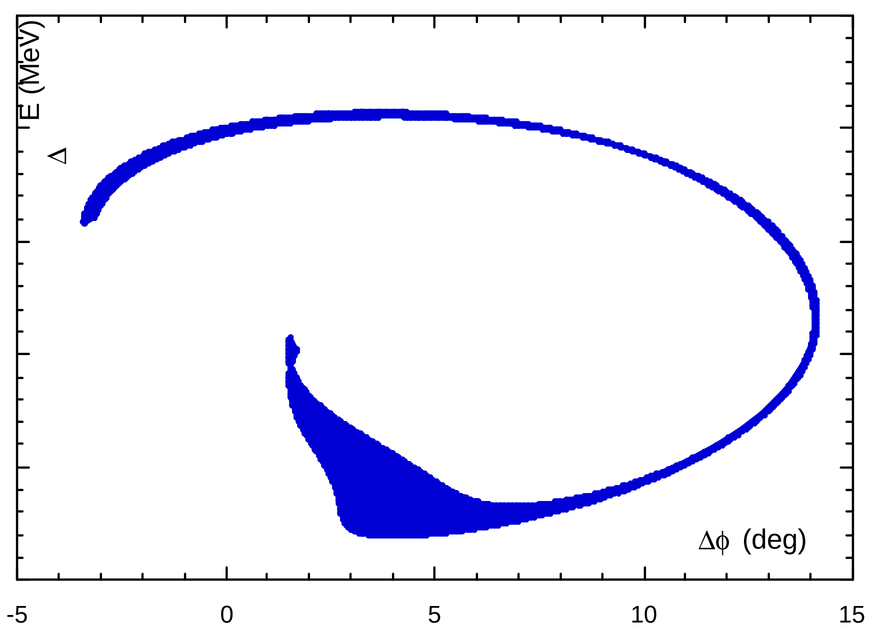
For proton beams, because of the phase slippage and because of the change of the dynamic behaviour of low-β cavities as the energy increases, even when the vector sum is kept perfectly constant, the individual cavity voltages can fluctuate with large amplitudes. We could however envisage to feed individually the cavities at the low energy part of the SC linac & to feed groups of cavities by common klystrons at the high energy part, where phase slippages are lower and cavities have closer dynamic properties. For example, groups of 8 cavities only above the 2nd sector (above 200 MeV)

⇒ Input energy offset

fluctuation of the individual cavity voltages though the vector sum is well controlled by the feedback loops (input energy offset of 0.5%)



Amplitude of the 8 cavity voltages for the last group



Energy & phase deviation for all bunches at linac end

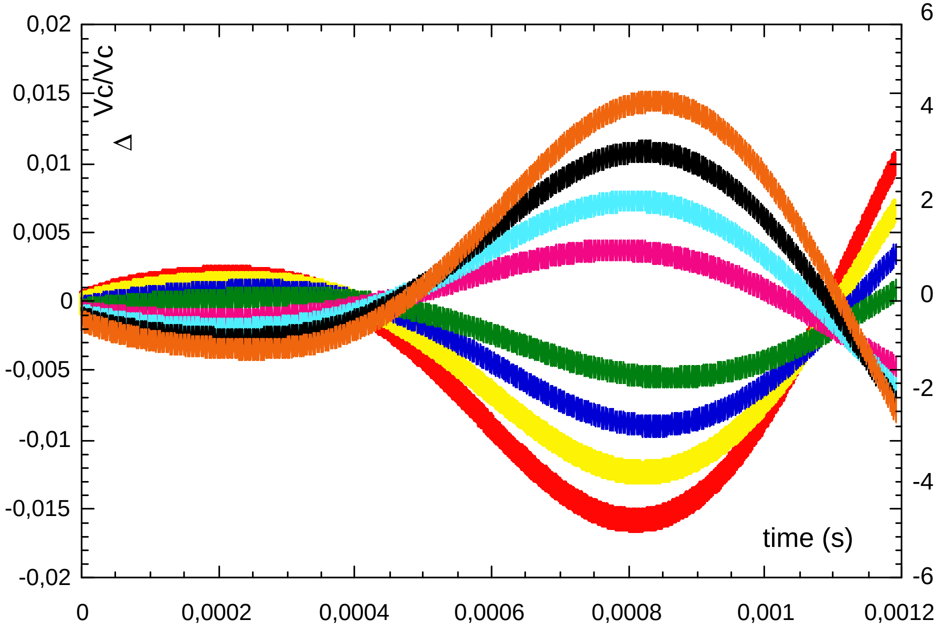
⟹ Lorentz forces effects

fluctuation of the individual cavity voltages though the vector sum is well controlled by the feedback loops

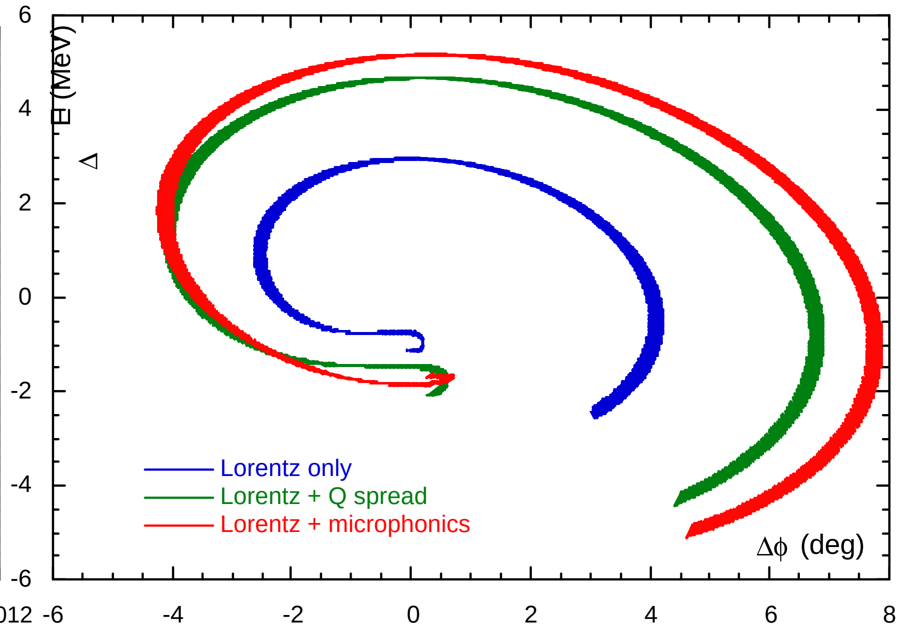
K=8, 4 Hz/(MV/m)^2 for the β=0.65, 0.86 cavities

additional effects of microphonics (40Hz oscillation with 100 Hz amplitude) and of a spread in external Q given by the power couplers (Q-spread of 20%)

The total energy deviation at linac end is this once lower than 1%



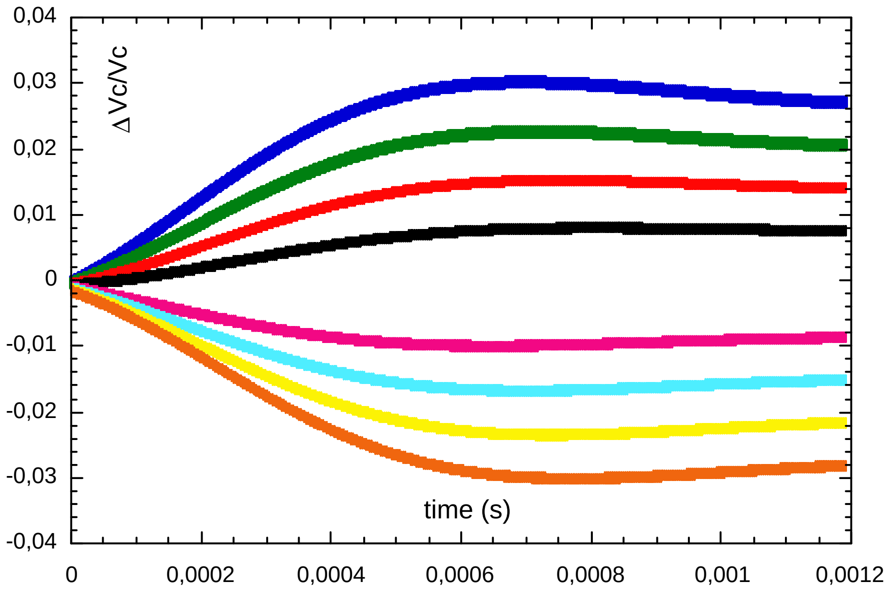
Amplitude of the 8 cavity voltages for the last group
(Lorentz forces detuning only)



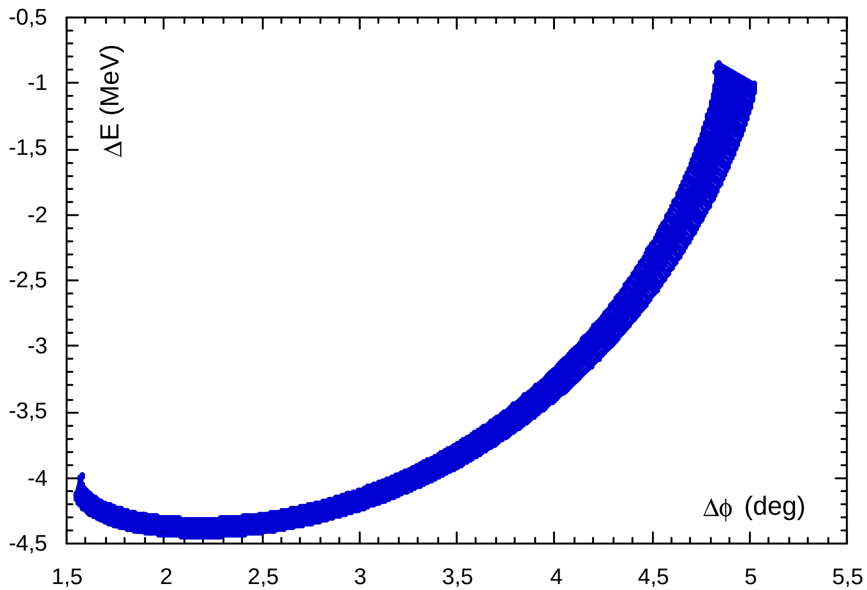
Bunch Energy and phase deviation at linac end
(Lorentz forces detuning
+ microphonics or Q-spread)

For example, groups of 8 cavities only above the 3rd sector (above 450 MeV)

⇒ Input energy offset

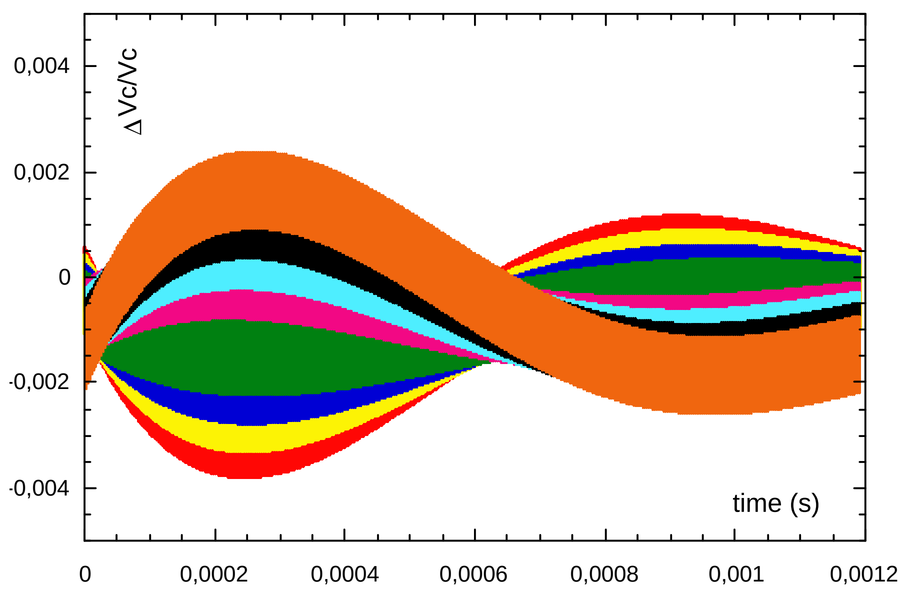


Amplitude of the 8 cavity voltages for the last group

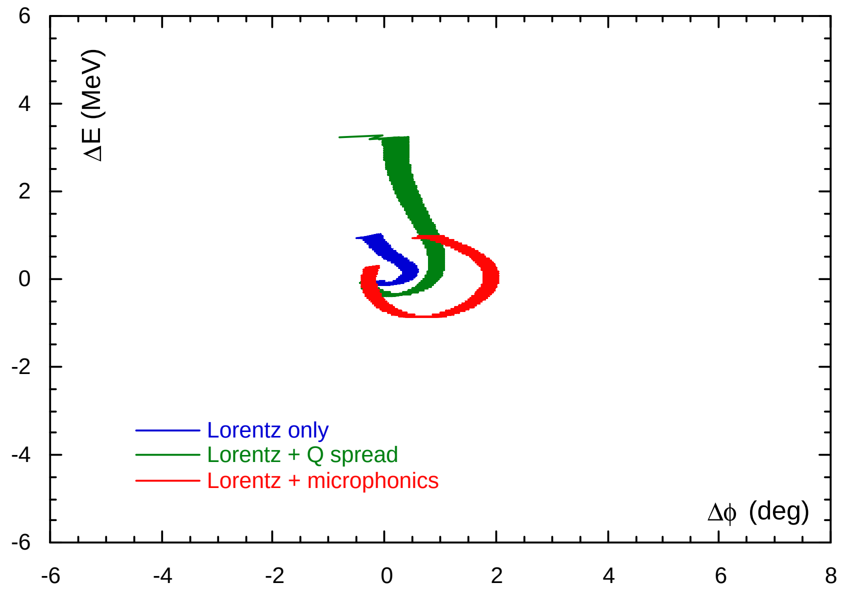


Energy & phase deviation for all bunches at linac end

⇒ Lorentz forces effects



Amplitude of the 8 cavity voltages for the last group
(Lorentz forces detuning only)



Bunch Energy and phase deviation at linac end
(Lorentz forces detuning
+ microphonics or Q-spread)

CONCLUSION

The **systematic energy modulation**, enhanced by transient beam-loading effects within a multi-cell cavity, looks actually harmless (about 10^{-3}) by using SC cavities with low number of cells and not too small intercell coupling (respectively 5 and around 1% in this study)

Besides, the impact of various error sources on energy stability in a typical SC proton linac has been studied by means of a simulation code, which integrates the coupled differential equations governing both cavity field & beam-cavity interaction

When each cavity has its own RF feedback system, the cavity voltages can be very well controlled, providing energy spreads at the linac end
well below the specifications

However, **groups of multiple cavities driven by common klystrons** and controlled by the vector sum, give rise to significant energy fluctuations and should be only used at sufficiently high energy, when phase slippage is low and the dynamic properties of the grouped cavities become similar